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THE VISIBILITY OF POINT SOURCES AS A FUNCTION OF BACKGROUND LUMINANACE, TARGET LUMINANCE, ECCENTRICITY, WAVELENGTH, AND FLICKER RATE

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14. ABSTRACT

The existing visibility literature was reviewed to determine how thresholds for detection of point-source targets vary as a function of target luminance, wavelength, eccentricity, and flicker rate as well as background luminance. After reviewing over 1500 papers and/or abstracts dealing with the above parameters, data from 14 studies were converted into a common luminance metric ($cd.m^{-2}$), adjusted for target size, and grouped into four luminance ranges (scotopic, low photopic, and two higher photopic ones), three eccentricity ranges (centered around 0°, 30° and 60°), and CW and three flicker ranges (1-2 Hz, 3-4 Hz, and 8-12 Hz). The results of the review showed that contrast thresholds decrease from ~25% at scotopic levels to around 2% at higher photopic levels. Thresholds increase by 2-3 log units from the fovea to 60° off-axis, except at scotopic levels where sensitivity is relatively flat across eccentricity (and even slightly lower at 30° off-axis). Thresholds for flickering targets were slightly lower (by 0.5 log units) than for static ones, with the optimal flicker rate dependent on luminance (e.g., sensitivity is best for lower flicker rates at low luminances but is best for higher frequencies at high luminances). Aside from wavelength, whose effects can be modeled by means of the v-lambda (photopic) and v'-lambda (scotopic) spectral sensitivity curves, the two biggest influences on visibility by far are background luminance and eccentricity.

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visibility, contrast sensitivity, detection, visual threshold, luminance, flicker, visual field, eccentricity

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1. INTRODUCTION

Visibility for a very small source of light - hereafter referred to as a "point source"[1] - reflects a complex interaction of many factors, including the size and luminance (which relates to perceived brightness) of the source, the luminance of the ambient background, the color (wavelength) and flicker frequency of the source, and the eccentricity of the source in the visual field relative to the fovea (the central 5° of the retina that supports the highest visual resolution).[2] The standard measure of visibility is the visual threshold, generally referred to as the point at which a subject can detect a light at least 50% of the time against a background.

At moderate-to-bright ambient luminances (i.e, from dawn/dusk to bright daylight), visibility for most stimuli increases quasi-linearly as a function of target contrast. Contrast refers to the luminance of the source relative to the background luminance ($\Delta L/L$). For threshold visibility, this fraction is a constant ratio over a wide range of background luminance. Weber's law, first enunciated by the German scientist, Ernst Heinrich Weber (1795-1878), states that the increase in stimulus which is necessary to produce a just noticeable difference in sensation bears a constant ratio to the stimulus from which the difference is noted. Weber's Law holds generally in the range of "photopic" vision. In this range, the cone photoreceptors in the retina drive human vision, as the rod photoreceptors are mostly bleached (i.e., saturate) when the background luminance reaches 3 candelas per meter squared ($cd.m^{-2}$), as would be the case at dawn or dusk.[3] The cones predominate in the fovea and respond optimally to 555-nm (yellowish) light, which falls midway between the peaks of the spectral sensitivities of the two predominant cone types (medium- and long-wavelength). The cones have good temporal and spatial resolution, which is why visibility peaks in the fovea for small target sizes (~2°) and moderate-to-high temporal frequencies (~8-15 Hz). Because the number of cones falls off precipitously outside of the center of the fovea, threshold increases dramatically beyond 1-2° eccentricity for small targets. For example, $\Delta L/L$ for point sources on photopic backgrounds is ~0.02 at the fovea but exceeds 1.0 by 7° eccentricity (Akerman & Kinzly, 1979). However, it has been shown that by adjusting target size for the amount of cortical area representing the visual world at each eccentricity[4] basic visual functions remain relatively constant across the visual field (Rovamo, Virsu & Nasanen, 1978).

From total darkness to about 0.001 $cd.m^{-2}$—a range known as "scotopic vision"—visibility largely reflects the contribution of the more sensitive rod photoreceptors. Rods possess better spatial and temporal summation but correspondingly poorer spatial and temporal resolution than do cones, and they also are comprised of only one type whose spectral sensitivity peak lies in the blue-green range around 510 nm. The optimal flicker rate for detection is about 1-2 Hz and, because the rods are absent from the fovea but are most dense in the mid-periphery, scotopic

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[1] A point source is defined in this report as any stimulus that subtends less than 5' of visual arc (1.5 mrad) on the retina (Laser Institute of America, 2001).

[2] The 1° center of the fovea, known as the fovea centralis, is sometimes referred to as the fovea itself.

[3] The candela per meter squared ($cd.m^{-2}$) is the international standard measure of luminance: a 1 cd source subtends 1 m^2 of area on a sphere with a radius of 1 m that intersects a 1 steradian cone of light emanating from the source.

[4] This relationship is known as the cortical magnification factor, which, in turn, highly correlates with retinal ganglion-cell density. Both cortical area and ganglion-cell density decrease in a Gaussian manner with eccentricity, so that larger stimuli are required in peripheral vision to yield equivalent visual performance.

visibility is greatest around 20°. Small targets are relatively harder to detect at night as a function of contrast, and the increment threshold for small targets in terms of target visibility (in absolute $cd.m^{-2}$) remains constant despite large changes in adapting scotopic luminances.

In the range of 0.001 $cd.m^{-2}$ to 10 $cd.m^{-2}$—known as "mesopic" vision—both rods and cones contribute to visibility. As adapting luminance increases in this range, humans become progressively more sensitive to small targets and to wavelengths approaching 550 nm. The peak flicker sensitivity increases above 1-2 Hz, and the sensitivity of the fovea relative to the periphery progressively increases until, at 0.001 $cd.m^{-2}$, the fovea achieves a greater sensitivity than the mid-peripheral retina. Because the effects of so many different parameters are changing, it is in the mesopic range that visibility is most difficult to model.

The "duplex" (rod-cone) theory of vision provides an acceptable framework to understand visibility, but there is no comprehensive model to predict visibility in the mesopic range for all of the parameters listed earlier. It is necessary, therefore, to review the actual visual threshold literature to make specific predictions. The purpose of the present study was to gather all relevant published, accessible, and usable data to estimate visual thresholds for point sources for the four major factors that all interact with each other: adapting luminance, eccentricity, flicker rate, and wavelength. This data may then be used to make predictions of the visibility of outdoor light sources with different combinations of these factors.

2. METHODS

In addressing the basic visibility literature, an initial review of major vision textbooks—particularly key chapters in the *Handbook of Human Perception and Performance* (Boff, Kaufman & Thomas, 1986) and its related *Engineering Compendium* (Boff & Lincoln, 1988)—was conducted. This was initially supplemented by a search for the terms "visual threshold" AND ("spatial summation" OR "temporal summation" OR "wavelength" OR "eccentricity" OR "flicker" OR "adapting luminance") for each the following databases: *Medline, PsychInfo, Annals of the New York Academy of Sciences, Biological Sciences, Aerospace Database, SPIE, and National Transportation Safety Board Civil Aviation Accidents.* Subsequent searches of over one dozen more basic and applied databases—including those of the *Defense Technical Information Center* and the *Transport Research Institute*—rounded out the literature review.

Well in excess of 1500 titles and/or abstracts were obtained (1155 from just *Medline* and *PsychInfo* alone). A total of 159 articles of interest were initially compiled from the combined databases, which were later reduced to 64 relevant articles that were found in local libraries or requested from other libraries. After scanning these articles, a final list of 25 articles was derived that was reviewed by a team of Northrop Grumman Information Technology, AFRL/HEDO, and Karta Technologies, Inc. vision experts. Only one obviously relevant paper—a University of Michigan Technical Report by Blackwell and MacCready (1958)—could not be obtained in time to be entered into the visual threshold database. Upon final review of the 25 articles, data from only 14 papers were ultimately entered into the visual threshold database. These papers, summarized in Appendix 1, represent 13 empirical data sets and a single set of model data (from Akerman & Kinzly, 1979) that was based on unpublished data of Hammill and

Sloan.[5] The remaining eleven papers were discarded because 1) their data were not in photometric units and could not be easily converted to photometric units, 2) they did not include sufficient information concerning one or more of their visual parameters, or 3) their parameters lay outside the ranges listed below.

Threshold data from the 14 final studies were converted to $cd.m^{-2}$ from $cd.ft^{-2}$, millilamberts (mL), footlamberts (fL), and trolands (td) and apostilbs (asb)[6]. In the case of flickering stimuli, threshold was defined as the difference between the peak luminance and average luminance of the flicker (i.e., one-half of the modulation depth). The thresholds were determined for three parameters: *background luminance* (0.001 $cd.m^{-2}$, 1.0 $cd.m^{-2}$, 1000 $cd.m^{-2}$, and 10,000 $cd.m^{-2}$); *flicker rate* (1, 3, and 10 Hz); and *eccentricity* (0°, 30°, and 60°). These parameters were chosen in consultation with collaborating scientists from the Lincoln Laboratories of the Massachusetts Institute of Technology, with the adaptation luminances corresponding to nighttime, dawn/dusk, daytime cloudy, and daytime sunny ambient sky brightnesses (Hood & Finkelstein, 1986, Table 5.1). Because many of the 14 papers did not include data for these specific parameters, we slightly broadened the range for each parameter. The ranges for the eccentricity parameter were expanded to 0-6°, 24-36°, and 48-72° for 0°, 30°, and 60°, respectively, while the ranges for the three flicker rates were: 1-2 Hz, for 1 Hz; 3-4 Hz, for 3 Hz; and 8-12 Hz, for 10 Hz. Ranges for each background luminance were broadened to: 0.0001-0.001 $cd\text{-}m^{-2}$, for 0.001 $cd.m^{-2}$; 1-10 $cd.m^{-2}$, for 1.0 $cd.m^{-2}$; 100-1000 $cd.m^{-2}$, for 1000 $cd.m^{-2}$; and >1500 $cd.m^{-2}$ for 10000 $cd.m^{-2}$. If a threshold for a background luminance fell into a particular range, then its $\Delta L/L$ contrast value was adjusted to the specific background luminance value for that range (e.g., the ΔL for 3 $cd.m^{-2}$ would be divided by three to yield the corresponding threshold at 1 $cd.m^{-2}$).[7] If more than one data point in a study fell into a particular background luminance range, only the one closest to the specified luminance was retained.

Two other restrictions were placed on the data set: 1) viewing duration had to be at least 200 ms, to allow for maximum temporal summation to occur; and 2) the size of the target could be no more than 3° in diameter. Because a wide range of target sizes were included in the database--ranging from less than 1’ of visual arc to 180’ (3°)—adjustments were made to each data point to equate it to the threshold at 3.6’ of arc (i.e., just inside the point-source range). These adjustments were done in two different ways. For the lowest background luminance, the data were adjusted using the Blackwell (1946) data, which included seven target sizes, the largest of any data set. Although the Blackwell data were collected from foveal presentations, its correction factor was also applied to the 30° and 60° data at 0.001 $cd.m^{-2}$, since no other more applicable target-size data were available. The VIDEM model (Akerman & Kinzly, 1979) was used to adjust for target size for the other three background luminances, since it was designed to

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[5] The major difference between the Hammilll/Sloan data and the VIDEM predictions is a 1.33 “field factor”, which helped to bring the VIDEM model in line with aircraft visibility data obtained from field measurements (Akerman & Kinzly, 1979). In order to compare the VIDEM predictions with other laboratory data, we removed this field factor before the VIDEM data were entered into our analysis.

[6] The following conversions were used: 1 $cd.m^{-2}$ = 1 td/pupil area; = 0.314 mL; = 0.29 fL; = 10.75 cd.ft-2; = 3.42 asb.

[7] The major exception to this scheme was the inclusion of data from Riopelle and Bevan (1953), who measured thresholds in the dark-adapted eye—i.e., below the lowest background luminance range in this analysis. However, Riopelle and Bevan (1953) was included because it was one of only two that measured thresholds at 60° eccentricity.

predict thresholds in the Weber range. Its threshold predictions as a function of eccentricity are based on the following formula:

$$Cr = 0.0352\theta^{0.24} + 0.584\,\theta^{1.6}/\alpha^2, \quad \theta \geq 0.8° \qquad \text{(Equation 1)}$$

Where Cr equals contrast threshold (i.e., $\Delta L/L$ with a 1.33 field factor), θ is retinal eccentricity in degrees, and α is target size in minutes of arc. In the case of foveal vision, θ is set at 0.8°.

The various corrections for some of the target sizes used in this study are shown in Table 1. It is evident that the effects of target size required the greatest adjustments foveally at the lowest background luminance and peripherally for the three photopic luminances. It is under these conditions that cones are less active and the large spatial summation capability of the rods predominates.

Table 1. Correction factors for visual thresholds as a function of background luminance and eccentricity (see text for details).

	Background luminance range (cd.m^{-2})			
Target size (′)	**0.001 (0°)**	**1-10,000 (0°)**	**1-10,000 (30°)**	**1-10,000 (60°)**
0.6	.028	.056	.028	.027
3.6	1	1	1	1
10	7.19	1.73	7.34	7.57
18	22.23	1.87	21.15	23.34
27.6	26.67	1.91	40.85	50.16
55	86.90	1.94	84.41	138.04

Finally, although target color (red, green, or white) is highly relevant to visibility, we found no usable data that specifically examined contrast threshold as a function of the wavelength of the stimulus. Hence, only thresholds for white light were included in the threshold database. Photometric threshold differences as a function of wavelength are rarely studied because photometric measures such as cd.m^{-2} already take into account very large differences in sensitivity to lights of different wavelengths.[8] Moreover, the spectral sensitivities of the visual

[8] Thresholds in cd.m^{-2} for each wavelength should theoretically be the same. The spectral sensitivity of the visual system must be taken into account to calculate how many lumens per watt (W) are in the light and, in turn, how much radiance (in W.cm^{-2}.steradian^{-1}) is needed to produce a particular luminance. Two main spectral sensitivity functions can be applied to the luminance ranges in our analysis: the photopic sensitivity curve (ν-lambda) for background luminances of 3 cd.m^{-2} and above and the scotopic sensitivity curve (ν′-lambda) for background luminances of .001 and below. Under photopic conditions, for example, there are 683 lumens.W^{-1} at the most sensitive wavelength (555 nm) and ~300 lumens.W^{-1} for the typical broadband light source (for a spectral efficiency of 300/683, or 0.44). The spectral luminous efficiency is 0.862 and 0.811 at 530 nm at photopic and scotopic levels, respectively, but it is only 0.107 and 0.0007 for 650 nm (red) at photopic and scotopic levels, respectively. Hence,

system at a given background luminance appear to hold for both static and flickering stimuli (Pokorny & Smith, 1986, Figure 8.7), for small-to-moderate target sizes (<10°) (Kokoshka & Adrian, 1985), and across eccentricities when target size is scaled (Kuyk, 1982).

3. RESULTS

The threshold mean from the 14 studies as a function of background luminance, eccentricity, and flicker rate are listed in Appendix 2. The greatest amount of usable data was for static stimuli in the fovea (where 7-10 points were obtained for each background luminance). Only VIDEM model predictions (Reference #1 in Appendices 1 and 2) were available at 30° and 60° for static stimuli, and flicker data for 0° were only available at 1 cd.m^{-2} and 1000 cd.m^{-2}. No thresholds for flickering stimuli were available at 30° and 60°.

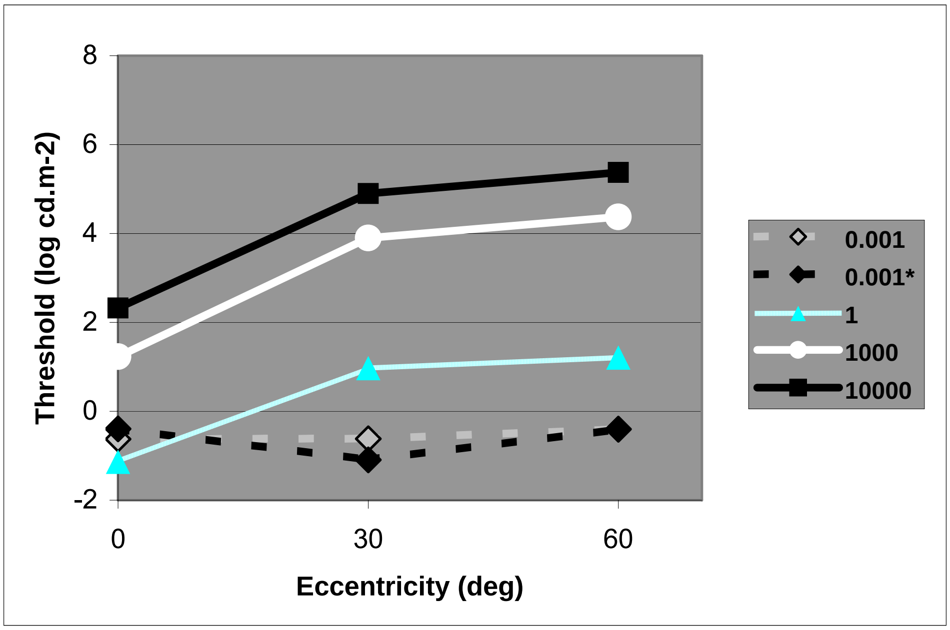

Figure 1. Visual increment threshold as a function of background luminance (shown in legend in cd.m^{-2}) and eccentricity. The 0.001 line is based on all available data, while the 0.001* line is based only on data from Poppel and Harvey (1973) and Riopelle and Bevan (1953). See text for details.

The variation of increment thresholds with background luminance and eccentricity, in log units, is shown in Figure 1. Except at 0.001 cd.m^{-2}, thresholds increased nonlinearly from the fovea to the periphery, increasing from 0° to 60° by slightly over 2 log units at 1 cd.m^{-2} and by ~3 log units at 1000 cd.m^{-2} and 10,000 cd.m^{-2}. Figure 1 shows that thresholds remained approximately flat across retinal eccentricity at 0.001 cd.m^{-2}. However, this is partly due to the fact that the 0° data were distorted because five of its nine threshold points were acquired by Blackwell (1946), who reported generally lower thresholds than did other researchers. When comparing visibility as a function of eccentricity only for the two studies that measured thresholds at all three locations (Poppel & Harvey, 1973; Riopelle & Bevan, 1952)—listed as 0.001* in Figure 1—the

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a 650-nm light must be generated by a source that is >1000 times more powerful than a 530-nm source to appear equally visible at night.

data show a reduced threshold at 30° relative to 0°, as predicted from the greater rod density at 30°.

It is worth noting that the VIDEM model predicts thresholds well at 1 cd.m^{-2}—within the range of its source data—but tends to overestimate thresholds for higher background luminances by about 3-4 times. For example, the average threshold at 1000 cd.m^{-2} was estimated as 17.13 cd.m^{-2}, with the 48.8 cd.m^{-2} VIDEM threshold included (see Appendix 2). Without VIDEM, the threshold would have been 11.85, or 24% of the VIDEM estimate. At 10,000 cd.m^{-2}, the threshold without the VIDEM prediction would have been 164.56 cd.m^{-2}, or about 34% of the VIDEM threshold of 488.88 cd.m^{-2}.

Visual thresholds as a function of flicker rate (static/0 Hz, 1 Hz, 3 Hz, and 10 Hz) and background luminance (1, 1000, and 10,000 cd.m^{-2}) at 0° eccentricity are shown in Figure 2. The data show that 1-Hz, 3-Hz, and 10-Hz flicker produced the lowest thresholds at 1 cd.m^{-2}, 1000 cd.m^{-2} and 10,000 cd.m^{-2}, respectively. There appears to be an elevated threshold for 1-Hz flicker at 1000 cd.m^{-2}, but this is an artifact due to one clinical perimetry study that reported very high thresholds (Casson et al, 1993) but only measured them at 1 Hz and 10 Hz.[9] To obtain a more accurate illustration of the relationship between flickering and static stimuli, thresholds from the only two studies (Anderson & Vingrys, 2000, 2002) that reported both static and flicker thresholds are shown in Figure 3. It is evident from these data that 4-Hz flicker at 1 cd.m^{-2} and 0° lowers the visual threshold for static stimuli by about 0.5 log units.

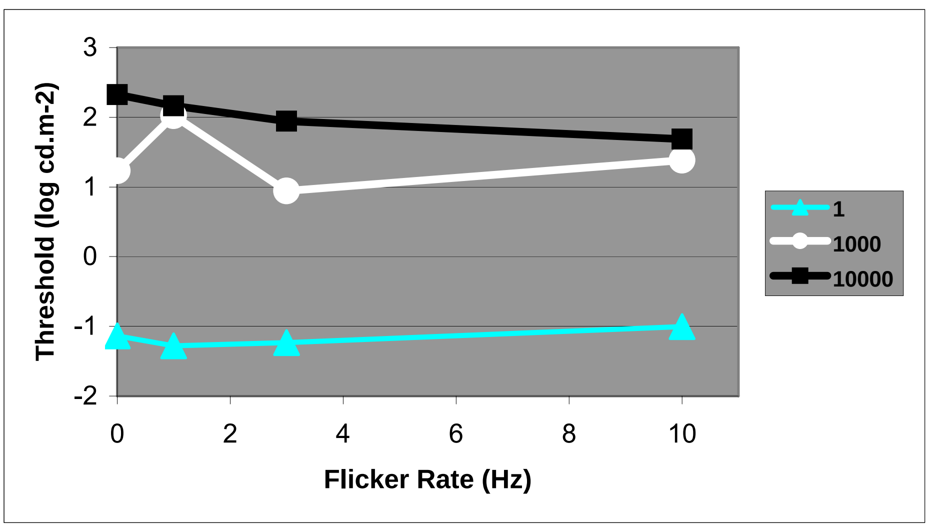

Figure 2. Visual threshold as a function of background luminance (shown in legend in cd.m^{-2}) and flicker rate.

Although there were no usable data concerning visual thresholds for flicker at the eccentricities reviewed in this analysis, there is reason to believe that flicker thresholds vary with eccentricity in much the same way as do thresholds for static stimuli. Data from Anderson and Vingrys (2002) show a comparable increase in thresholds from 0° to 15° for static and 4-Hz flickering

[9] Perimetry studies typically produce higher threshold values, because they use an ascending method-of-limits technique in which the stimulus starts below threshold and increases until it is just above threshold.

stimuli (Figure 4). The ~0.5 log increase in threshold from 0° to 15° is consistent with the data from Riopelle and Bevan (1952), Johnson, Keltner and Balestrrery (1981), and Poppel and Harvey (1973). Moreover, for small targets in the photopic range, the same trends for retinal eccentricity appear to hold for all flicker rates up to 10 Hz (Makela, Rovamo & Whitaker, 1994).

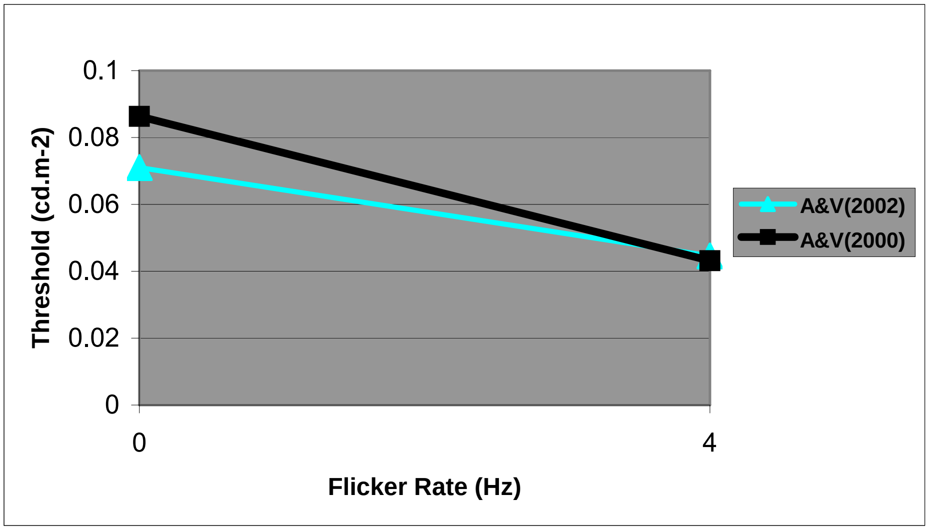

Figure 3. Visual thresholds for static and 4-Hz targets at 0° (from Anderson & Vingrys 2000, 2002).

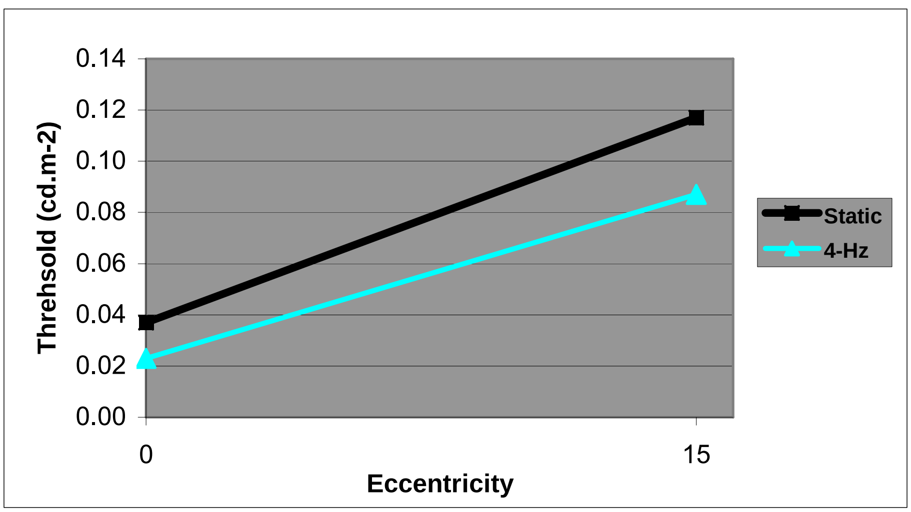

Figure 4. Visual thresholds for static and 4-Hz targets at 0° and 15° eccentricity (from Anderson & Vingrys, 2002)

4. DISCUSSION

The results of our review and analysis demonstrate that two major factors affect visibility thresholds for point sources: background luminance and eccentricity. Flicker, on the other hand, only modestly affects visuals threshold depending on the background luminance. The wavelength of the source does not directly affect photometric thresholds per se, but it does substantially affect how much irradiance in $W.cm^{-2}$ is needed for a source to achieve a particular luminance.

At least for photopic backgrounds beyond 100 $cd.m^{-2}$, threshold is a fairly constant percentage (~2%) of background luminance, and even at 1 $cd.m^{-2}$it only rises to 7%. Hence, the ability to see a point source of the same intensity varies dramatically from dawn or dusk to the middle of a bright day. For ambient backgrounds, visual thresholds are largely independent of background luminance below 0.1 $cd.m^{-2}$ and, indeed, absolute threshold may actually rise slightly for foveal stimuli (Figure 1). Hence, visual models such as VIDEM that assume a constant Weber fraction tend to underestimate visual thresholds at low ambient luminances and overestimate them at higher luminances.[10]

The other major influence on point-source thresholds is eccentricity in the visual field. The largest change occurs from 0° to 30° from the fovea, where our analysis shows that a 2.0-2.5 log increase in foveal threshold occurs in the high-photopic range. The increase from 30° to 60° appears somewhat smaller (~0.5-1.0 log) for this luminance range. The increase in threshold with eccentricity, related to the previously mentioned cortical magnification factor (Rovamo et al., 1978), may have been overestimated in our analysis since the only peripheral data at the higher background luminances were derived from the VIDEM predictions, which were higher than all other foveal data at 1000 and 10,000 $cd.m^{-2}$. Data from Johnson et al. (1981) and Poppel and Harvey (1973) suggest that the increase at 30° and 60° may be closer to 1.5 and 2.0 log units, respectively.

The effects of flicker are more complex and subtle than those of background luminance and eccentricity. The largest flicker effects occur at the highest background luminances, where thresholds for high flicker rates (8-12 Hz) are ~0.6 log units below that of 1-Hz flicker (Figure 2). However, a similar advantage occurs at 1 $cd.m^{-2}$ when only comparing 4-Hz flicker to static thresholds (Figure 3). Generally, flicker of increasing frequency enhances visibility as background luminance increases, with 1-2 Hz best at 1.0 $cd.m^{-2}$ and below, 3-5 Hz at 1000 $cd.m^{-2}$, and 8-12 Hz best at 10,000 $cd.m^{-2}$. Flicker duty cycle evidently has little effect, as long as the duty cycle of the flicker is less than 50% (Laxar & Benoit, 1993). Although flickering a stimulus improves visibility when average luminance is held constant, flicker has the practical disadvantage of requiring twice the peak source luminance for the same average luminance (assuming a 50% duty cycle). So, flicker may not be highly advantageous in many actual operational settings.

Wavelength also has an important influence on visibility, but it is expressed in terms of the irradiance at the source rather than photometric thresholds per se. The number of $lumens.W^{-1}$—the basis for deriving the irradiance required to produce a particular luminance in $cd.m^{-2}$—varies by as much as three orders of magnitude in moving from green to red under scotopic conditions (see Footnote #8). Hence, the power of a source under dim illumination must be ~1000 times greater in the red than green range to appear equally visible. At photopic luminances, this difference is smaller (an 8-fold greater sensitivity for green) but still striking.

Of course, one cannot equate laboratory-generated visual thresholds reviewed in this paper with those obtained even under optimal real-world conditions; rather, one must multiply the

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[10] Another well-known model of visibility—that of Adrian (1989)—is slightly less linear and overestimates high-photopic foveal thresholds by only a factor of 2-3 for 200-ms viewing times (Dr. Marc Green, personal communication, 15 Mar 04).

laboratory data by a “field” factor, usually between one and two (Akerman & Kinzly, 1979; Matchko & Gerhart, 1998), to account for such variables as psychological state (vigilance level, expectancies, etc.) and structure in the visual environment. Nor are point-source visibility thresholds necessarily good predictors of suprathreshold phenomena such as target detection in cluttered environments (Owsley, Ball & Keeton, 1995). Point-source thresholds may also not be highly applicable to thresholds for 1) sources larger than points, which are subject to complex spatial summation as a function of ambient luminance, eccentricity, and flicker (see Hood & Finkelstein, 1986, and related chapters in Boff et al, 1986), 2) spatially patterned stimuli (e.g., gratings), which are processed by spatially selective filters, or 3) “disability glare”, which can be defined as the disruption of visual function by an intense, suprathreshold light source that requires an extended image and may consequently favor the visual periphery to a relatively greater extent (Jennings & Charman, 1981).

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APPENDIX 1

Synopsis of Relevant Citations

1. Akerman & Kinzly (1979):

Akerman and Kinzly (1979) described the VIDEM model, which is based on data by Hammill and Sloan (1975, cited in Akerman & Kinzly, 1979). The VIDEM model makes predictions concerning target size, eccentricity (down to 0.8°), and background luminance. It was validated against actual aircraft detection and fared well against earlier models, assuming a 1.33 field factor. The VIDEM model is based on photopic luminances (specifically, 10 cd.m^{-2}) and was not considered usable for predicting threshold at .001 cd.m^{-2}.

2. Anderson & Vingrys (2000):

Anderson and Vingrys (2000) studied the interactions between flicker threshold and luminance pedestals for five subjects. They used a 0.5° white sharp-edged spot target at 0° and 15° and an exposure duration of 750 ms. Anderson and Vingrys (2000) measured increment thresholds as well as flicker (mean-to-peak) thresholds on a 4 cd.m^{-2} background for different-sized luminance pedestals ranging from 0 to 30 cd.m^{-2}. Their flicker rates were 4 Hz, 7.5 Hz, 12 Hz, and 20 Hz, with only the 4 Hz and 12 Hz data used in our analysis.

3. Anderson & Vingrys (2001):

Anderson and Vingrys (2001) studied the multiple interactions among flicker sensitivities with luminance pedestals. They used a 0.5° white sharp-edged spot target at 0^o and an exposure duration of 750 ms. They measured flicker (mean-to-peak) thresholds for different-sized luminance pedestals ranging from 0 to 21.5 cd.m^{-2} on 4 cd.m^{-2}, 14 cd.m^{-2}, and 25.5 cd.m^{-2} backgrounds. Only the data for the 30' target on a 0 cd.m^{-2} pedestal and a 4 cd.m^{-2} background were analyzed. The flicker rates were 4 Hz, 7.5 Hz, 12 Hz, 20 Hz, and 30 Hz, with only the 4 Hz and 12 Hz data used in our analysis. Data were taken from their Figure 1.

4. Anderson & Vingrys (2002):

Anderson and Vingrys (2002) studied increment thresholds for six subjects at 0° and 15° eccentricity for two different flicker frequencies (4 and 20 Hz) as well as a 0.5° static target at 4 cd.m^{-2}. Data were obtained from their Figure 1 (which presented the results from the first of their three experiments) and were limited to 0 Hz and 4 Hz and 0° eccentricity.

5. Blackwell (1946):

Blackwell (1946) measured visual thresholds from seven subjects for extended viewing times (15 s). The procedure was also modified so that minimum thresholds could be reasonably achieved. Target stimuli were always presented in the center of observation. Subjects indicated with a rotating handle whether they believed a target was present or not; a 50% correct score was used to determine visual threshold. Target diameters of 360' (3°), 121', 55.2', 18.2', 9.68', 3.6', and .595' were used. Background luminance levels ranged from 2 log ftL (342 cd.m^{-2}) to –5 log ftL (.000342 cd.m2) were used to estimate thresholds from 0.001–1000 cd.m^{-2}. Data, expressed in values, were taken from Table VIII, which presented interpolations from plots of arithmetical means from his third experiment.

6. Casson, Johnson & Nelson-Quigg (1993):

Casson et al. (1993) used temporal modulation perimetry to evaluate foveal and eccentric sensitivity with different age groups. A 2° LED stimulus was used and the bowl perimeter had a constant background luminance of 100 cd/m^2. The 43 normal subjects were divided into three age groups: 20-39 yrs, 40-59 yrs, and >60 yrs; only the data from the 20-39 group was used. Sensitivity was evaluated at four eccentricities (0°, 5°, 10°, and 20°) at three flicker rates (2 Hz, 8 Hz, and 16 Hz). Data were plotted in decibels (dB), defined as log sensitivity values (1 dB = 10[log (1/threshold contrast)] and then converted to ΔL/L.

7. Crawford (1937):

Crawford (1937) in one of many experiments reported in his paper, examined increment thresholds for two subjects for a 0.46° target against a white background of varying backgrounds ranging from <10^{-8} cd.m^{-2} to ~10^1 log cd.m^{-2}. He used a staircase procedure, with 50% visibility as his threshold. His data, originally presented in cd.ft^{-2}, were translated in cd.m^{-2} by multiplying by a factor of .094. The data subjected to our analysis were derived from his Figure 7.

8. DeLange (1958):

DeLange (1958) measured flicker threshold (sensitivity) as a function of adaptation luminance for a 2° target size. His adapting luminances, originally expressed in photons (trolands or td for his 2.8-mm pupil) were converted to cd.m^{-2}. The adapting luminances ranged from 0.06 to 1592 cd.m^{-2}. The difference between the peak and average luminance of the flicker (or one-half the modulation amplitude divided by the average luminance) was used to calculate ΔL/L. The ΔL/L values at 1.59 cd.m^{-2}, 159.2 cd.m^{-2}, and 1592 cd.m^{-2} were then used to estimate thresholds at 1 cd.m^{-2}, 100 cd.m^{-2}, and 10,000 cd.m^{-2}.

9. Faubert (1990):

Faubert (1990) measured thresholds for five flicker rates (1 Hz, 5 Hz, 10 Hz, and 15 Hz) as a function of eccentricity, adapting luminance, and target size. His adapting luminances were 3.4 cd.m^{-2} and 10 cd.m^{-2} and the targets sizes for his white stimuli ranged from 0.125° to 2.0°. His five eccentricities were 1.25°, 2.5°, 5°, 10°, and 20°. The 1-Hz, 5-Hz, and 10-Hz data for the .125° target size were analyzed at 3.4 cd.m^{-2}. His data were converted from log modulation sensitivity (1/% modulation) by first deriving the modulation depth and then taking the peak-to-average luminance (i.e., one-half the modulation depth) as the threshold.

10. Hejil, Lindgren & Ollson (1987):

Hejil et al (1987) assessed the variability in static threshold perimetry for the central field out to 30° eccentricity with a Humphrey perimeter whose adapting luminance was 10 cd.m^{-2}. A total of 95 normal subjects were initially tested; 88 of these returned for a second session after two months and 74 returned for a third session after four months. Ages ranged from 20 to 80 years. The age-corrected foveal threshold was 0.5 cd.m^{-2} and was ~6.5 cd.m^{-2} 30° off-axis for a 50-year-old normal subject. At 5°, the threshold had increased 5.5 dB (a factor of 3.5). Variability among individuals, test-to-test variability within individuals, and intra-test variability were all measured. The sensitivity decrement with age was found to be eccentricity dependent. The peak sensitivity was depressed for the older subjects and the falloff with eccentricity was also greater. Both within and between tests, variability for normal individuals increased with eccentricity from fixation.

11. Johnson, Keltner & Balestrery (1981):

In one of their two experiments, Johnson et al. (1981) employed static perimetry to measure thresholds for a white target between 0° and 30° at $1\text{-}2^{\circ}$ intervals. Three normal subjects were used. Their background luminances ranged from .00032 cd.m^{-2} to 3.18 cd.m^{-2}. An ascending methods of limits was used to determine thresholds, which typically produces higher thresholds compared to other techniques. The thresholds, expressed as $\Delta L/L$, were converted to cd/m^{-2} and extrapolated to the appropriate luminance range (.0003 cd.m^{-2} thresholds were used to estimate 0.001 cd.m^{-2} thresholds; 3.18 cd.m^{-2} thresholds were used to estimates 1 cd.m^{-2} thresholds).

12. Lamar, Hecht, Shlaer & Hendley (1947):

Lamar et al. (1947) obtained threshold values from one subject for rectangles varying in area from .5 to 800 square minutes of visual angle and length/width (l/w) ratios varying from 2 to 200. Targets could appear in one of four locations inside a 4° circle and around a central fixation dot; subjects reported to indicate where the target appeared. All targets appeared in the fovea, but the data were partly replicated with the fixation moved to 1.25° and 10° in the periphery. Two background luminance levels were used, 2950 ftL and 17.5 ftL. The only data used came from the 2950 ftL (10,089 cd.m^{-2}) background condition, the l/w ratio of 2, and smallest length (4.48').

13. Poppel & Harvey (1972):

Poppel and Harvey (1972) studied static thresholds (sensitivity) from one subject as a function of adaptation luminance and eccentricity using a 10' target. Their luminances, originally expressed in mL and converted to cd,m^{-2} by a factor of 3.18, ranged from .00027 to 2.7 cd.m^{-2}. The Weber fractions ($\Delta L/L$) for the lowest and highest luminances were used to predict the target luminance for adapting luminances of 0.001 and 1 cd.m^{-2}.

14. Riopelle & Bevan (1953):

Riopelle and Bevan (1953) investigated the absolute sensitivity to light across the visual field in the dark-adapted eye for eight subjects. The target was a 1° diameter white spot of light presented for 750 ms. The target was presented at azimuths every 22.5 degrees and at eccentricities from 0° to 56°. Highest sensitivities (i.e., lowest thresholds) were for temporal retinal locations, which were the only locations used in our analysis. Thresholds ranged from approximately -4.0 to -4.8 log cd m^{-2}. The shape of the curve roughly followed the retinal density of the rods, with the lowest sensitivities at the fovea and the highest sensitivities between 10° and 30° of eccentricity.

APPENDIX 2
VISUAL THRESHOLD DATA

					STATIC				FLICKER	
								1.000	3.000	10.000
	Degrees		ref#	*Correction*	Corr. Threshold	Means	SD	Corr. Threshold	Corr. Threshold	Corr. Threshold
Adapt. Lumin	Eccentricity	Target size (')								
0.001	**0**	**1**	5	*0.028*	0.018					
		4	5	*1.000*	0.018					
		10	5	*7.194*	0.018					
		18	5	*22.233*	0.018					
		55	5	*86.896*	0.018					
		10	11	*7.194*	1.124					
		10	13	*7.194*	0.791					
		28	7	*42.855*	0.133					
		60	14	*86.896*	0.009					
						0.248	**0.416**			
	30	**10**	11	*7.194*	0.562					
		10	13	*7.194*	0.158					
		60	14	*86.896*	0.001					
						0.241	**0.289**			
	60	**10**	13	*7.194*	0.791					
		60	14	*86.896*	0.002					
						0.397	**0.558**			
1.000	**0**	**1**	5	*0.055*	0.086					
		4	5	*1.000*	0.048					
		8	9	*1.597*				0.089	0.074	0.094
		10	5	*1.733*	0.015					
		18	5	*1.874*	0.010					
		55	5	*1.937*	0.007					
		4	1	*1.000*	0.049					
		28	7	*1.914*	0.021					
		10	11	*1.733*	0.217					
		10	13	*1.733*	0.173					
		30	4	*1.919*	0.071				0.045	
		30	2	*1.919*	0.086				0.043	0.100
		10	10	*1.733*	0.088					
		120	8	*1.943*				0.016	0.010	0.019
		30	3	*1.919*					0.121	0.182
						0.073	**0.065**	**0.052**	**0.058**	**0.099**
	30	**10**	11	*7.342*	16.392					
		4	1	*1.000*	7.884					
						12.138	**6.016**			
	60	**4**	1	*1.000*	23.788					
		10	13	*7.565*	8.473					
						16.130	**10.830**			
1000.000	**0**	**1**	5	*0.048*	26.913					
		4	5	*1.000*	19.011					
		10	5	*1.733*	8.142					
		18	5	*1.874*	6.499					
		55	5	*1.937*	6.436					
		4	1	*1.000*	48.802					
		28	7	*1.914*	4.112					
		120	6	*1.943*				195.625		43.785
		120	8	*1.943*				14.576	8.745	4.859
						17.131	**16.228**	**105.100**	**8.745**	**24.322**
	30	**4**	1	*1.000*	7883.714					
						7883.714				
	60	**4**	1	*1.000*	23788.149					
						23788.149				
10000.000	**0**	**1**	5	*0.055*	226.216					
		4	5	*1.000*	154.170					
		10	5	*1.733*	79.388					
		18	5	*1.874*	64.986					
		55	5	*1.937*	54.977					
		5	12	*1.270*	407.657					
		4	1	*1.000*	488.022					
		120	8	*1.943*				145.757	87.454	48.586
						210.774	**174.098**	**145.757**	**87.454**	**48.586**
	30	**4**	1	*1.000*	78837.135					
						78837.135				
	60	**4**	1	*1.000*	237881.491					
						237881.491				